NOTES ON RAILWAY ELECTRIFICATION.

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It is difficult to realise that less than a century has elapsed since the first Commercial Steam Railway started, and not more than 25 years since the earliest attempts at electric traction. During these 25 years the field of electric traction has been enlarged, until it is now co-terminus with that of steam. From the early small tramway developments we have now passed to the development of heavy electric traction.

For the purpose of heavy traction three systems of electrification have been proposed—three-phase alternating current, single-phase alternating current, and direct current. For the sake of conveniently arranging the argument of these notes, the three-phase system is referred to first. This system has its own field of application, and in it has been fairly successful. Starting with the first Valtellina line, practically all the electrification in the northern part of Italy, under the Italian State Railways, has been carried out on a three-phase system, and in one case in America, viz., the Great Northern Electrification in the Cascade Mountains, it has been used. The reason for its adoption is to be found in the possibility of regeneration of electric energy from the motors back to the line. This feature is of importance, not so much on account of the saving of energy as on account of the saving in brake shoe wear when the railway has to be operated over heavy mountain grounds. However, now that regeneration is possible with either of the other two systems, the 3-phase system has lost to a great extent any importance that it originally had. One point greatly in its favour is that 3-phase induction motors are used on the rolling stock. These motors are, of course, particularly rugged on account of the simplicity of their construction; on the other hand the variation speeds possible for the train are extremely limited.

The arrangement of the overhead line is also attended with certain difficulties owing to the necessity of having at least two contact lines for each track. By single-phase electrification we understand a single-phase alternating current distribution, while the motors of the rolling stock may be single-phase commutator motors of various types, polyphase induction motors if phase converters are used, or direct current motors if Mercury Rectifiers are used. In its original application only single-phase commutator motors were used, but experience has shown that such motors are costly to maintain, and extremely uncertain in operation. As a result the advocates of single-phase have sought for means by which more rugged motors can be used, while keeping the single-phase form of distribution. Two solutions have apeared. The first in commercial operation is known as the Split Phase system; in this system the contact line supplies single-phase energy to the locomotive transformer. Between the transformer and the motors is installed a phase converter. This is being used on the Norfolk and Western Railway Electrification in Virginia, U.S.A.

By the use of the Split-Phase system, power may be regenerated and returned to the line, but up to the present it is not known whether it is successful or not.

In the Mercury Rectifier, single-phase energy is drawn from the contact line, and a Mercury Rectifier is interposed between the locomotive transformer and the motors. Direct current series motors are used. This method has been proposed and is being tentatively tried on one car, but is not in commercial use.

The objections to the single-phase system are so many and so great that it is difficult to believe that it will ever be generally used. It is fairly extensively adopted on the Continent of Europe, due in the main to German influence. In America it has been adopted in several instances, but has been discarded in favour of the direct current in most of them. The advocates of single-phase argue that by its use high voltage distribution may be adopted with a minimum of copper. They also point out that the whole electrification is simple, the scheme being single-phase generation in the power house, and direct distribution at the voltage of generation without the interposition of substations. On paper this looks perfectly reasonable, but in practice it is found to be otherwise. In the first place it has not been found practicable to build large single-phase generators. It is believed that the largest single-phase generator built is 8,000 k.V.A., in Bittefeld, in Germany. In America three-phase generators have been used, from which single-phase energy is drawn. Obviously the output of such a generator is only about 60% of what it would be operating as a three-phase machine.

The distribution of high voltage single-phase energy has been attended with results, always injurious and sometimes disastrous to the telephone and telegraphic circuits in its vicinity. Electrostatic and also electro-magnetic induction both effect low voltage circuits in the vicinity, producing in them voltages which are sometimes dangerous and at all times interfere with their proper operation. The electrostatic induction can be, and is screened. So far as the writer knows there is no new method yet discovered of efficiently protecting the low voltage circuits against the electro-magnetic interference.

The electrical equipment of rolling stock is always very much heavier and more expensive for single-phase than for direct current. This usually more than offsets the initial first cost of substations for the D.C. system, especially in the case of main lines and fairly dense traffic.

The system which has given the greatest satisfaction, both from operating and financial standpoints, is that known as the direct current system. In this, three-phase energy is generated and transmitted at any desired voltages to substations and converted to direct current energy which is distributed to the contact system. Motors of the rolling stock are direct current series motors. There has been a logical sequence of development from the earliest tramway systems, operating at 600-V. direct current, to the interurban system, operating at 1200 or 1500-V., to the heavy main line electrification at 2400 or 3000-V. The 1200-V. system, the pioneer of high voltage direct current traction, was developed for a line near Pittsburg, the originator being Mr. James Bryan. Actually speaking, the line which was in operation first was the Indianopolis and Louisville Traction Co.'s line. operating between the two cities mentioned. The earliest extensive electrification of 1200-V. was the Washington, Baltimore, and Annapolis line, operating between those three cities. This line originally was operating at 6600-V. single-phase, but so many difficulties were encountered that it was decided to change over to the 1200-V. direct current system. Owing to the fact that experience as to cost, maintenance, and so forth, was obtained from both systems, this line always proves interesting as a means of comparing the direct current with the single-phase system under identically similar conditions. Many other interurban systems operating at 1200 or 1500-V. have been installed in America, but it was not until 1913 that the first 2400-V. line was placed in operation. This was the Butte, Anaconda and Pacific, a short line, 26 miles long, over which large quantities of heavy freight was transported. Originally it was operating as a steam system, but it was felt that economy could be effected by converting to an electric form of haulage. The conditions were somewhat peculiar. There was a substation in existence at Butte, and one at Anaconda, consequently it was very desirable to select a voltage which would permit these two substation buildings to be utilised, and at the same time to keep the amount of copper of the feeder system down to a reasonable quantity. The voltage selected was 2400-V., and since for this particular line no multiple unit cars were being considered, no difficulty was met in equipping the rolling stock. The line has been in operation since September, 1913, for a period of two years, and the economy of operation has been remarkable. The total net saving amounts to more than 20% of the investment or total cost of electrification. This figure does not, of course, take into account the increased capacity of the line, improvement to the service, and the more regular working hours for the crews. The comparison also shows that the tonnage per train has been increased by 35%, while the number of trains has been decreased by 25%, with a saving of 27% in the time required per trip.

The success of the Butte, Anaconda, and Pacific has led to the conversion of part of the trans-continental system of the Chicago, Milwaukee, and St. Paul to the electric operation. The voltage chosen for this is 3000-V. direct current. The initial electrification covering 113 miles of the main line between Three Forks and Deer Lodge in Montana, is the first step towards the electrification extending from Harlowtown, Montana, to Avery, Idaho, a total distance of roughly 450 miles, aggregating about 850 miles of track, including yards and sidings. This scheme is but the beginning of the electrification from Harlowtown to the Pacific Coast, a distance of roughly 900 miles. The plans are of especial interest, as it is the first attempt to install and operate electric locomotives on tracks extending over several engine divisions. It is under these circumstances that the full advantage of electrification is to be secured. The various terminal and tunnel installations, for example, New York Central of New York, Pennsylvania Railroad of New York, and Michigan Central Railroad, have been made necessary by reason of local conditions.

The electrification of Chicago, Milwaukee, and St. Paul road is undertaken purely on economic grounds, with the expectation that superior operating results with electric locomotives will effect a sufficient reduction in the present cost of steam operation to return an attractive percentage on the large additional investment required. The power supplied from this scheme is obtained from the Montana Power Co., which controls 10 water power developments and one small steam power station. The railway contract for power is based on a 60% load factor, and the price is .536 cents per k.W. hour, delivered at some 5 points along the line at

100,000-V. three-phase, 60-cycles. The average distance between substations is about 35 miles, notwithstanding that the first installation is over the Rocky Mountains, and embraces about 21 miles of 1 in 50 grade westbound, and 11 miles of 1 in 60 grade eastbound. With these extreme distances between substations, and considering the heavy traffic and small amount of feeder copper projected, it is apparent that so high a potential as 3000-V. D.C. permits of a minimum investment in substation apparatus and considerable latitude in location.

The substations will be of the indoor type, transformers being three-phase, oil-cooled, and reducing from 100,000 Volts primary to 2300 Volts secondary, at which potential the synchronous motors will operate. The transformers are rated 1900 and 2500 k.V.-A., and are provided with four 2½ per cent. taps in the primary, and 50 per cent. starting taps in the secondary.

The motor-generator sets comprise a 60-cycle synchronous motor driving two 1500 Volt direct current generators connected permanently in series for 3000 Volts. The fields of both the synchronous motor and direct current generators are separately excited by small generators direct connected to each end of the motor-generator shaft. The direct current generators are compound wound, will maintain constant potential up to 150 per cent. load, and have a capacity for momentary overloads up to three times their normal rating. To insure good commutation on these overloads, the generators are equipped with commutating poles and compensating pole-face windings. The synchronous motors will also be utilised as synchronous condensors, and it is expected that the transmission line voltage can be so regulated thereby as to eliminate any effect of the fluctuating railway load.

The location and equipment of the several substations is as follows:—

Station.	Mile from Deer Lodge.	No. of Units.	Kw. per Unit.	Total.
More	17·1	2	2,000	4,000
Janey	50·5	3	1,500	4.500
Piedmont	77·9	3	1,500	4.500
Eustis	120·6	2	2,000	4,000

The trolley constructed is of the catenary type, in which a 4/0 trolley wire is flexibly suspended from a steel catenary supported on wooden poles, the construction being bracket wherever track alignment will permit and cross-span on the sharper curves and in yards. Steel supports instead of wooden poles are used in yards where the number of tracks to be spanned exceeds the possibilities of wooden pole construction. Work in this direction will be completed in the summer of 1915, ready for operation in the autumn on the delivery of the first locomotives.

As the result of careful investigation and experiments, a novel construction of trolley is installed, composed of the so-called twin-conductor trolley. This comprises two 4/0 wires, suspended side by side from the same catenary by independent hangers, alternately connected to each trolley wire. This form of construction permits the collection of very heavy current by reason of the twin contact of the pantograph with the two trolley wires, and also insures sparkless collection under the extremes of either heavy current at low speed or more moderate current at very high speeds. It seems that the twin-conductor type of construction is equally adapted to the heavy grades calling for the collection of very heavy currents, and on the more level portions of the profile where maximum speeds of 60 m.p.h. will be reached with the passenger trains, having a total weight of over 1000 tons. The advantage of this type of construction is due partly to the greater surface for the collection of current, but largely to the very great flexibility of the alternately suspended trolley wires, a form of construction which eliminates any tendency to flash at the hangers either at low or high speed.

The locomotives are of especial interest for many reasons. They are the first locomotives to be constructed for railroad service with direct current motors designed for so high a potential as 3000 Volts. They weigh approximately 260 tons, and have a continuous capacity greater than any steam or electric locomotive yet constructed. Perhaps the most interesting part of the equipment is the control, which is arranged to effect regenerative electric braking on down grades. This feature as yet has never been accomplished with direct current motors on so large a scale. The general characteristics as proposed are tabulated below:

Total weight	260 tons
Weight on drivers	200 tons
Weight on each guiding truck ..	30 tons
Number of driving axles	8
Number of motors	8
Number of guiding trucks	2
Number of axles per guiding truck	2
Total length of locomotive	112 ft.
Rigid wheel base	10 ft.
Voltage of locomotive	3000
Voltage per motor	1500

H.P. rating 1 hour each motor .	430
H.P. rating continuous each motor	375
H.P rating 1 hour complete locomotive	3440
H.P. rating continuous complete locomotive	3000
Trailing load capacity, 2 per cent. grade	1250 tons
Trailing load capacity, 1 per cent. grade	2500 tons
Approximate speed at these loads and grades	16 m.p.h.

The Chicago, Milwaukee, and St. Paul Railway, from Harlowton to the coast, crosses four mountain ranges: the Belt Mountains at an elevation of 5768 ft., the Rocky Mountains at an elevation at 6350 ft., the Bitter Root Mountains at an elevation of 4200 ft., and the Cascade Mountains at an elevation of 3010 ft. The first electrification between Three Forks and Deer Lodge calls for locomotive operation over 20.8 miles of 2 per cent. grade between Piedmont and Donald at the crest of the main Rocky Mountain Divide, so that the locomotives will be fully tested out as to their capacity and general service performance in overcoming the natural obstacles of the first engine division.

The initial contract calls for nine freight and three passenger locomotives having the above characteristics and similar in all respects, except that the passenger locomotives are provided with a gear ratio permitting the operation of 800-ton trailing passenger trains at approximately 60 m.p.h., and will, furthermore, be equipped with an oil-fired steam heating outfit for the trailing cars. The interchange ability of all electrical and mechanical parts of the freight and passenger electric locomotives is considered to be of very great importance from the standpoint of operation and maintenance.

The cab consists of two similar sections extending practically the full length of the locomotive. Each section is approximately 52 feet long, and the cab roof is about 14 feet above the rail, exclusive of the housings for ventilation. The trolley bases are about 5 feet above the roof, owing to the unusual height of the trolley wire, which is fixed at a maximum elevation of 25 feet above the rail. The outer end of each cab contains a compartment for the engineer, while the remainder is occupied by the electric control equipment, train heater, air brake apparatus, etc.

The eight motors for the complete locomotive are type GE-253-A. This motor has a normal one-hour rating of 430 h.p., with a continuous rating of 375 h.p. The eight motors thus give the locomotive a one-hour rating of 3400 h.p., and a continuous rating of 3000 h.p. The drawbar pull available for starting trains will aproximate 120,000 lbs., at 30 per cent. coefficient of adhesion.

Each motor is twingeared to its driving axle in the same manner as on the Butte, Anaconda, and Pacific, the Detroit River Tunnel, and the Baltimore, and Ohio locomotives, a pinion being mounted on each end of the armature shaft. The motor is of the commutating pole type and has openings for forced ventilation from a motor-driven blower located in the cab.

The freight locomotives are designed to haul a 2500-ton trailing load on all gradients up to 1 per cent., at a speed of approximately 16 m.p.h., and this same train load unbroken will be carried over the 1.66 and 2 per cent. ruling grades on the west and east slopes of the Rocky Mountain Divide, with the help of a second similar freight locomotive acting as pusher. Track provision is being made at Donald, the summit of the grade, to enable the pusher locomotive to run around the train and be coupled to the head end to permit electric braking on the down grade. In this case, the entire train will be under compression and held back by the two locomotives at this head end, the entire electric breaking of the two locomotives being under the control of the motorman in the operating cab of the leading locomotive. It is considered that electric braking will prove very valuable in this mountain rail-roading; for, in addition to providing the greatest safety in operation, it also returns a considerable amount of energy to the substations and transmission system, which can be utilised by other trains demanding power. In this connection, the electric locomotive will have electric braking capacity sufficient to hold back the entire train on down grade, leaving the air brake equipment with which they are also equipped to be used only in emergency and when stopping the train. There is, therefore, provided a duplicate braking system on down grades, which should eliminate a considerable part of break-downs, wheel and track wear, and overheating, with consequent reduction in maintenance and improvement in track conditions.

With the completion of the remaining engine divisions, it is proposed to take advantage of the possibilities afforded by the introduction of the electric locomotive by combining the present four steam engine divisions into two locomotive divisions of approximately 220 miles length, changing crews, however, at the present division points. As the electric locomotive needs inspection only after a run of approximately 2000 miles, requires no stops for taking on coal or water, or layover due to dumping ashes, cleaning boilers or petty roundhouse repairs, it is expected that the greater flexibility of the locomotive so provided will result in considerable change in the method of handling trains now limited by the restrictions of the steam engine.

While this line constitutes the most recent of the heavy main line conversions, it is interesting to note the continued success of the New York Central Suburban electrification, which includes the electrification of the main Hudson River Division as far as Harmon, a distance of about 35 miles from the Grand Central terminal.

The present electric zone of the New York Central Railroad includes 52 miles of electrified road, totalling about 251 miles of third rail on a single track basis. Electric trains on the main line run to Croton, a distance of 34 miles, and to North White Plains on the Harlem division, a distance of 24 miles from the terminal. All through passenger trains are handled by electric locomotives within the electric zone, the change being made at Harmon on the main line, about a mile south of Croton, and at North White Plains on the Harlem division. The suburban passenger traffic is handled by multiple unit car trains.

Electric power is generated in duplicate steam turbine stations, one located at Port Morris, on Long Island Sound, and the other at Glenwood, near Yonkers, on the river front. Each power plant contains four 5000 k.W. vertical Curtis Steam Turbines, generating 3-phase, 25-cycle current at 11,000 Volts. The two power stations are electrically cross connected.

Three-phase, alternating current is transmitted at 11,000 Volts to nine substations. The high tension current is carried through duplicate sets of insulated copper cables in ducts, in the thickly populated sections, and over bare copper cables on steel poles in the less densely settled districts.

There are sixteen miles of conduit transmission and 42 miles of pole lines.

The substations contain stepdown transformers, synchronous converters, and the necessary switching apparatus. Storage batteries floating on the line are also used as indicated in the following table. Current is fed to the underrunning third rail from the sub-station busbars at 660 Volts.

SUB-STATION CAPACITY.

Sub-station	No. of Units.	Capacity of Each.	Total K.W.	K.W. Hourly Rating Storage Battery.	Miles from Terminal.
No. 1—50th Street ...	4	1,500	6,000	3,100	·4
No. 2—Mott Haven ...	3	1,500	...	...	...
	1	2,000	6,500	2,500	5·5
No. 3—Kingsbridge ...	3	1,000	3,000	2,000	9·5
No. 4—Glenwood ...	3	1,000	...	...	...
	1	2,000	5,000	...	15·6
No. 5—Irvington ...	3	2,000	6,000	...	21·7
No. 6—Ossining ...	3	1,000	3,000	1,500	30·3
No. 7—Bronx Park ...	3	1,000	...	...	...
	1	2,000	5,000	1,500	9·3
No. 8—Tuckahoe ...	3	1,000	3,000	...	16·1
No. 9—White Plains...	3	1,000	3,000	...	22·9
	31		40,500		

All local service between the Grand Central Terminal and Croton on the main line, and White Plains on the Harlem division, is taken care of by multiple unit cars which are operated in trains of from three to twelve cars usually made up in the proportion of two motor cars to one trailer. Suburban express trains are made up of from two to ten motor cars. There are now in service 192 motor cars and 19 trailers, having a seating capacity of 64 passengers. Each motor car is equipped with two GE-69, 200 h.p. motors and type M control. The motor cars completely equipped weigh approximately 57 tons.

The following table gives a comparison of the service performed by these cars and the former steam service.

COMPARISON OF SUBURBAN TRAIN SERVICE.

Items.	Hudson Steam.	Division Electric.	Harlem Steam.	Division Electric.
Date of Time Table	Dec., 1906	Dec., 1913	Dec., 1906	Dec., 1913
Number of Trains per 24 hours ..	54	44	59	64
Number of Trains per maximum hour	5	7	8	10
Fastest Schedule Time between Terminals, minutes	65	68	51	46
Average Schedule Time for Local Express, minutes	72·4	72·0	56·6	51·2
Average Schedule Time for Locals, minutes	79·2	76·6	64·5	59·1

There are sixty-three electric locomotives in service, all equipped with gearless bipolar motors. The following table contains the principal data as to capacity, weight, speeds, etc.

PASSENGER LOCOMOTIVES.

No.	Classification.	Wgt. on Drivers. Tons.	Continuous Rating. T.E. Lbs.	Continuous Rating. M.P.H.	Continuous Rating. Coef. Adhes.	Continuous Rating. H P.	One Hour Rating. T.E. Lbs.	One Hour Rating. M.P.H.	One Hour Rating. Coef. Adhes.	One Hour Rating. H.P.	Maximum Rating. T.E.	Maximum Rating. Coef. Adhes.	Date Initial Operation.
1	484-E-228-4GE84-600	71	5,000	60·5	3·5	800	21,000	38·8	14·8	2,200	42,600	30	1906
34	484-E-226-4GE84-600	70	5,000	60·5	3·6	800	21,000	38·8	15·0	2,200	42,000	30	1908
12	484-E-244-4GE84-600	71	5,000	60·5	3·4	800	21,000	38·8	14·2	2,200	44,400	30	1909
10	4444-E-236-8GE92-600	118	11,400	57·5	4·8	1.760	17,200	50·5	7·3	2,320	70.800	30	1913
6	4444-E-266-8GE91-600	133	14,000	54·5	5·3	2,000	20.000	49·0	7·5	2,600	80,000	30	1914
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Classification.—The first group of figures indicates the wheel arrangement on the successive trucks including both guiding and motor trucks. The letter "E" is used to denote electric locomotives. The second number gives the total locomotive weight in thousands of pounds. The remainder of the classification gives the number, type and voltage of the motors.

The repair shops are located at Harmon and at North White Plains, where all locomotives and multiple unit equipments are inspected and repaired.

Maintenance figures on the multiple unit equipments show an average of about 1.9 cents per car mile.

The electric locomotive service in New York and vicinity includes switching in yards and terminals, hauling shop trains about six miles, and a main line express service on one division of 34 miles, and another division of 24 miles. The average cost for maintenance, including inspection, repairs, renewals, cleaning, and painting, varies from month to month; but the average, covering a period of eight years, is not far from 3½ cents per mile. The maintenance during the year 1914 was about 4⅓ cents per mile. The increase was caused by the renewal in one year of driving wheel tires on the first 35 locomotives.

It will be seen by comparing the services of the Chicago, Milwaukee, and St. Paul with the New York Central electrification, that we get the very extremes of traffic met with on railroads; the New York Central in the electrified portion constitutes dense branching traffic, while the Chicago, Milwaukee, and St. Paul has one long single line. Between these two extremes will lie practically any line for which electrification is proposed. It is very doubtful whether so low a voltage as 600 would again be used for a steam road electrification; in fact on all the new rolling stock of the New York Central, the motors are insulated for 1200-V., indicating that the engineers of that road contemplate at some time changing over to 1200-V. While we do not suggest that 3000-V., which is adopted for the Chicago, Milwaukee, and St. Paul is the extreme upper limit of voltage for electric railways, it would seem from the studies made on that road, that considering the present state of the art of manufacture, it is the maximum economical voltage. However, for practically all conditions of electrification the economical voltage will be found to lie between 600 and 3000. It is quite probable that for all ordinary conditions and for all cases in which multiple unit cars are used, the maximum economical limit will be about 1500 or 1600 Volts.